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IMPROVED CORRELATIONS FOR AUGMENTOR STATIC STABILITY (POSTPRINT)

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Improved Correlations for Augmentor Static Stability

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Flame stability is critical to the operational performance of combustion systems in propulsion and power generation. Current predictive tools for flame stability are based on decades-old empirical correlations that have limited applicability for modern combustor designs. Recent advances in computational fluid dynamics (CFD) and advanced combustion diagnostics have provided new insight into the fundamental processes that occur in these flows. Reacting-flow CFD has yet to mature to a level where it can be practically applied as a design tool for this problem. This paper describes a new methodology for analyzing flame stability intended to provide designers with a significantly improved near-term predictive capability. Our predictive methodology is based on a Damköhler number (*Da*) approach. Simplified CFD calculations are used to calculate relevant flow timescales, and reactor model calculations are used to characterize the important chemical timescales in the system. These timescales are used to form a *Da* number that is used to determine stability. Unlike existing stability correlations, which are typically based on global parameters, the new methodology predicts stability based on the local *Da* field. In addition, the new methodology is expected to reduce the requirement for on empirical inputs when developing a stability model. The methodology is demonstrated using a simple rig configuration. Future work will involve application of the methodology to more complex, realistic augmentor conditions.

Nomenclature

CFD	=	Computational Fluid Dynamics
D	=	Flame Holder Characteristic Dimension
Da	=	Damköhler Number
ε	=	Turbulent Dissipation
k	=	Turbulent Kinetic Energy
LBO	=	Lean Blow Out
LES	=	Large-Eddy Simulation
P	=	Combustor Inlet Pressure
PDF	=	Probability Density Function
PSR	=	Perfectly-Stirred Reactor
PaSR	=	Partially-Stirred Reactor
RANS	=	Reynolds-Averaged Navier Stokes
Re	=	Reynold's Number
St	=	Strouhal Number
T_{ad}	=	Adiabatic Flame Temperature
τ_{chem}	=	Chemical Timescale
τ_{flow}	=	Flow Timescale
T_o	=	Initial Temperature for Ignition Delay

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U = Combustor Inlet Velocity
u' = Turbulence Intensity
Φ = Equivalence Ratio

I. Introduction

Flame stability is critical to the operational performance of combustion systems in propulsion and power generation. Existing design systems in industry today are based on parametric testing and generic, simplified correlations. Empirical correlations for predicting flame stability parameters such as lean blowout (LBO) are often based on *global* inputs, such as inlet temperature and mean flow. This type of approach understandably has limited accuracy, especially for state-of-the-art systems that push the performance envelope.

Recent advances in Computational Fluid Dynamics (CFD) and combustion diagnostics have provided new insight into the significant processes affecting augmentor stability. Recent data have allowed flame dynamics near blowout to be directly observed with high spatial and temporal resolution. For example, the interaction of vortices shed from an augmentor flameholder with the recirculation zone has been identified as a key process associated with blowout and both static and dynamic stability under certain conditions[1,2,3,4]. CFD has provided new insight into these flows; however, the technique is often impractical to apply as a design tool due to computational cost and complexity[5].

The objective of this research program is to develop computationally tractable reduced-order models for predicting augmentor static stability that incorporate insight into physical processes obtained via advanced diagnostics and CFD calculations. These models will provide combustor and augmentor designers with a new tool that can help bridge the gap between outdated correlations based on global inputs and complex reacting flow CFD calculations and/or expensive parametric experimentation.

II. Background

The design of combustion systems existing in industry today is based on empirical testing and generic, simplified correlations. Current tools have limited applicability to modern combustor designs[6]. Several of the correlations in use are analyzed in detail below. Experimental data for LBO fuel-to-air ratio are collected and a correlation for predicting LBO is developed based on the global parameters varied in the experiments, such as inlet velocity. Many critical factors are not incorporated into the correlations, and the correlations generally do not extrapolate well beyond the parameter space on which they were defined. Not surprisingly, these correlations often poorly predict LBO, especially when used to predict state-of-the-art augmentor designs that push the performance envelope and utilize unique geometries.

The cost of full-scale qualification of combustion systems has increased substantially such that parametric testing of design iterations to solve operability and performance shortfalls, has created significant system development costs. A design system capable of predicting the influence of the geometry and design features on operability and performance could save millions of dollars in program development costs and help ensure that engine systems are highly optimized. An improved design system must capture the influence of dimensionality and *local* interactions that drive the behavior of the system.

CFD techniques, such as RANS and Large-Eddy Simulation (LES), have been applied to solve reacting flows for simplified configurations[7-13]. A recent AIAA special issue was dedicated to this topic[5]. CFD methods for reacting flows have significant computational cost, so that they are not currently a practical tool for designers. However, reacting flow CFD can be used to generate a large quantity of spatially and temporally resolved data that cannot be readily obtained experimentally. For this reason, reacting flow CFD is useful for developing insight into these flows that can be applied to reduced-order models that are computationally tractable.

The purpose of this research program is to bridge the gap that exists between current design tools and available diagnostic and computational capabilities. Our approach involves use of tractable, mature computational techniques to calculate several timescales relevant to stability. The timescales are used to form a Damköhler number, *Da*, that is used to predict stability. Damköhler number approaches, based on global inputs, have been developed in the past. The primary distinction between previous efforts and the current research is that *local Da* values in the regions that determine stability are calculated. Below, we review existing stability correlations present an improved

methodology for predicting stability, demonstrate the methodology using LBO data for an augmentor rig, and discuss challenges and next steps for this approach.

III. Existing Stability Correlations

When early researchers began studying these flows in the 1950's, they primarily approached the problem through direct experimentation[14-16]. Researchers conducted parametric studies based on global parameters, such as inlet velocity and temperature. They then used their experimental results to derive stability correlations for the prediction of blowout equivalence ratio as a function of global inlet parameters. A loose physical justification for the correlation was typically given; however, they are highly empirical in nature. Because experiments are costly and time consuming, the parameter space on which early stability correlations are based is limited. We refer to these correlations here as the empirical class of correlations.

Two commonly used empirical correlations are those of DeZubay[14] and King[16]. The basis for DeZubay's correlation was a series of rig experiments using disk shaped flameholders in a circular duct. DeZubay's rig was subscale with a diameter of 7 cm. DeZubay's experiments all involved hopane fuel. Inlet velocity, pressure, and the diameter of the disk were varied. Velocity was varied from 12 to 168 m/s and pressure was varied from 0.2 to 1 atm. Based on the measure LBO data, DeZubay derived a correlation parameter for predicting LBO Φ. DeZubay's parameter is of the form:

$$\frac{U}{P^{0.95}D^{0.85}} \tag{1}$$

More recently other researchers have modified the DeZubay parameter to include a term for inlet temperature. When plotted against this parameter, DeZubay's LBO data collapsed to a curve, a stability loop, that can be used to predict lean and rich blowout.

King's empirical correlation is based on conditions that are more representative of an actual augmentor. JP-4 fuel was used and measurements were made at elevated inlet temperature. King's experiments spanned inlet velocities from 122 to 198 m/s, pressures from 0.35 to 0.85 atm, and inlet temperatures from 700 to 1,033 K. King's rig was full-scale with a diameter of 65 cm. A single flameholder geometry was considered, so that no geometry information appears in the correlation. King's correlation parameter is:

$$P^{0.324}T^{1.07}(750-U)^{0.252} \tag{2}$$

King's correlation predicts LBO only, and the stability curve has a much different shape from DeZubay's curve due to the way that the parameter is formed: DeZubay's parameter increases with U, whereas King's parameter decreases with increasing U.

The limitations of the empirical correlations are numerous. The correlations are derived based on a limited parameter space and do not generally apply outside of that parameter space. For example, DeZubay's correlation cannot be expected to perform well for non-disk shaped flameholders or configurations with widely varying blockage ratios. King's correlation clearly cannot predict a configuration with $U > 750$ (fps units are used when evaluating the correlation). Neither correlation can account for different fuel types or other potentially significant parameters such as inlet turbulence intensity. These types of correlations are used by designers as a starting point but cannot be expected to accurately predict new configurations. Modified versions of the empirical correlation parameters have been developed by engine manufacturers but the modified forms are considered proprietary and are not openly disclosed.

More recently, researchers have improved the physical descriptions used to develop stability correlations with the hope of developing more accurate, general stability correlations. In the improved physical description, stability is seen as being determined by competition between a flow (τ_{flow}) and chemical timescale (τ_{chem}). We refer to this class of correlations as the timescale correlations. Notable timescale correlations include those of Ozawa[17] and Plee[18]. Ozawa's stability correlation is actually only a small part of a large paper on the properties of high-speed combustion systems, and is nicely summarized in a recent paper by Driscoll[19].

The success of the Damköhler number approach depends on how the timescales are defined and calculated. In Ozawa's correlation, τ_{flow} is formed from the inlet velocity and the characteristic dimension of the flameholder. This timescale is said to represent the gas residence time in the shear layer. The chemical timescale is described as the ignition delay time of the mixture. τ_{chem} and τ_{flow} are used to form a Damköhler number:

$$Da = \frac{\tau_{flow}}{\tau_{chem}} \tag{3}$$

When LBO Φ is plotted against *Da*, a typical stability loop results. Unlike the empirical correlations, Ozawa's correlation is derived using multiple data sets in the literature for different conditions, so it is expected to apply more generally than the empirical correlations. Despite the improved physical description, Ozawa's correlation remains highly empirical. Ozawa's τ_{chem} is determined by plotting τ_{flow} and LBO Φ data and working backwards to determine τ_{chem}, which is a rather indirect method for determining τ_{chem}.

Plee developed one of the most advanced timescale correlations in the literature[18]. In addition to chemical and flow timescales, Plee's includes timescales to account for mixedness and fuel droplet penetration into the reaction zone. For well-mixed conditions with a fully vaporized fuel, Plee's correlation simplifies to a form very similar to Ozawa's—stability is determined based on competition between a flow and chemical timescale. Like Ozawa, Plee uses a global flow velocity and flameholder dimension to define τ_{flow}. Plee extends the development of the chemical timescale concept beyond Ozawa by identifying that ignition delay time data typically follow an Arrhenius form and calculating τ_{chem} directly. Plee's approach remains highly empirical however, in that the Arrhenius constants and the functional relationship between τ_{flow} and τ_{chem} used to predict stability are empirically derived.

IV. Limitations of Existing Correlations

Existing correlations are unsatisfactory for several reasons. The physical justification for existing correlations is based on local processes, but the local processes are estimated from global parameters. Calculating local parameters directly would increase accuracy and make the methodology more general. In addition, the fundamental assumption that a single global flow and chemical timescale determine stability is an oversimplification for modern flameholders. For a multi-component flameholder with a complex, three-dimensional geometry, multiple timescales at various spatial locations may be important. A discussion of the limitations of the use of global quantities to predict stability has been discussed by Nair and Lieuwen[4].

Another shortcoming of existing stability correlations is that they are highly dependent on empirical data. The empirically derived parameters do not generally extrapolate well to new configurations, so that experimentation is required when applying an existing correlation to validate or modify an existing correlation. For example, King's parameter is based on JP-4 fuel. In order to apply this correlation to a configuration involving a different fuel, such as JP-10, new blowout data would need to be collected in order to empirically derive the functional relationship between King's parameter, Eq. (2), and LBO Φ.

A final limitation is that the conditions for the experiments that form the basis for the early correlations is not always well defined. There is often confusion between inlet velocity and the mean velocity at the flameholder which takes into account the blockage. The inlet turbulence field is often not provided or accurately described, as is the quality of the mixedness of the fuel and air. The lack of a concise description of the conditions for which the existing correlations were derived limits the ability to extrapolate these correlations to new conditions. Recent advances in diagnostics and CFD have greatly improved our ability to resolve with high spatial and temporal resolution the flow fields and scalar concentrations in these types of flows.

V. Improved Correlation Methodology

We present a new methodology for developing stability correlations. The same fundamental physical description that is used in the timescale correlations is retained—stability is determined using a Damköhler number formed from a relevant flow and chemical timescale. However, unlike existing timescale correlations, the timescales are not evaluated using global quantities, but are evaluated locally. In addition, instead of deriving the timescales empirically, we exploit the power of CFD and modern chemical kinetics solvers to provide timescale data. These

techniques allow for evaluation of the local spatial distribution of *Da* in the reaction zone, as opposed to using a single, global *Da* to determine stability. The computational techniques required are straightforward and have relatively low computational cost.

For augmentors, it has been argued that the relevant flow time is either the flow residence time in the wake or the shear layer generated by the flameholder. In our approach, the turbulent flow field in the wake of the flameholder is calculated directly using unsteady Reynolds-Averaged Navier Stokes (RANS) CFD calculations of the non-reacting flow. For a particular geometry, this procedure can be repeated over a range of Reynolds numbers to generate a correlation for flow timescale based on CFD as opposed to experimental data.

The relevant chemical time for augmentor stability is typically described as an ignition delay time. Existing correlations do not directly calculate or estimate this timescale, it is back-calculated based on empirical data. In our approach, we calculate ignition delay times computationally using reactor models. For well-mixed conditions, the Perfectly-Stirred Reactor (PSR) model can be used. For poorly mixed conditions, the Partially-Stirred Reactor (PaSR) model can be used. Information about the mixing status can be obtained from the CFD calculations. Due to the low dimensionality of reactor models, ignition delay data can be calculated relatively easily, even for complex chemical mechanisms. This approach allows for large amounts of τ_{chem} data to be calculated for various fuels, vitiation levels, and inlet pressures.

To summarize our approach, low-order CFD calculations are used to determine the local velocity field in the wake of the flameholder. Reactor models are used to calculate chemical timescales for the flow. A *Da* field in the wake of the flameholder is calculated and used to determine stability. A key question that arises when evaluating stability based on local *Da* values is what location or location(s) determine stability? This is an open question requiring future investigation. Below we demonstrate our methodology by making predictions for a v-gutter flameholder in a bluff-body flameholder rig.

VI. AFRL In-House Research Rig

We demonstrate the methodology by generating a correlation for a premixed, propane-air, v-gutter configuration for which experimental data are readily available. The rig, shown in Fig. 1 below, has a rectangular cross section, 5" x 6", so that the flow is approximately two-dimensional. The flameholder considered here is an open v-gutter with 1.5" characteristic dimension. Our collaborators at Wright-Patterson Air Force Base have recently performed lean blowout measurements as a function of inlet velocity and temperature for propane fuel for this rig. Mean inlet velocities in the range 3.5 to 33 and inlet temperatures in the range 300 to 530 K. In addition, they provided inlet turbulence intensity data and have recorded a large volume of high-speed image data for observation of the blowout dynamics. An example is superimposed in Fig. 1. It should be noted that although we assume that the flow is well-mixed in the analysis below, there is some uncertainty as to whether the flow was actually well-mixed for the data presented below. These results should therefore be treated as a work in progress.

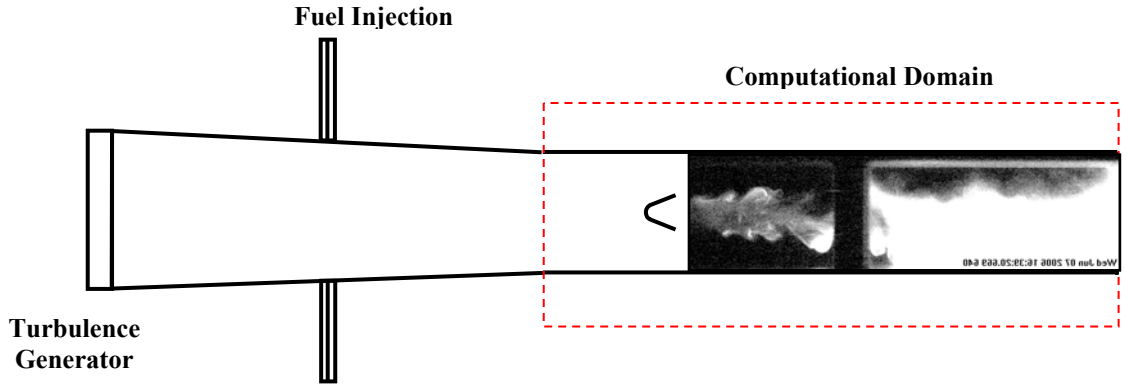

Figure 1. AFRL in-house research rig located at Wright-Patterson Air Force Base.

VII. Flow Timescale

We calculated the flow field for the Augmentor HIT rig using unsteady, two-dimensional RANS in FLUENT® with a k-ε turbulence model. The computational domain is shown in Fig. 2 below. Inlet turbulence intensity was provided experimentally, although the turbulence field can be calculated computationally by extending the domain further upstream in the flow. FLUENT simulations were performed for *Re* in the range 10,000 to 55,000. The structure of the flameholder wake and shear layer is shown in Fig. 2 below, which shows instantaneous and mean turbulence intensity (*u'*) fields for *Re* = 40,000. CFD calculations were validated based on the Strouhal number of the characteristic vortex shedding (*St* = 0.275) and by comparing mean and RMS velocity profiles with LDV data. In general, agreement between our CFD calculations and experimental data for the flow field is good.

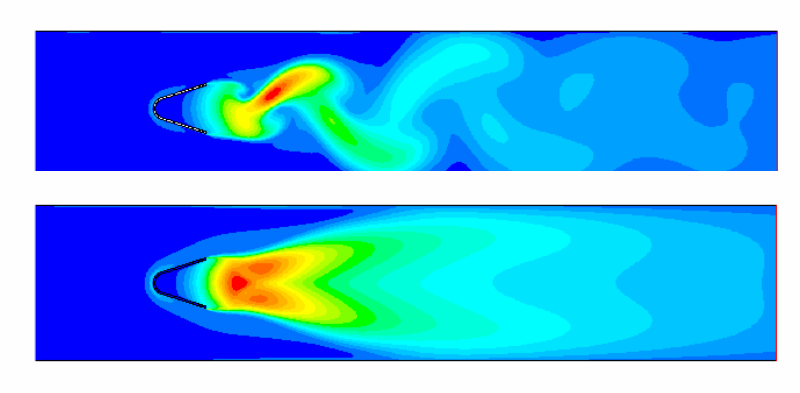

Figure 2. Instantaneous (top) and mean *u'* fields for the Augmentor HIT rig, *Re* = 40,000, showing the vortex shedding structure typical of a flameholder wake.

For the current demonstration, we used the ratio of turbulent kinetic energy (k) and dissipation (ε) to form the flow timescale, τ_{flow} = k/ε. This timescale is representative of the local rate of turbulent mixing. It should be noted that this definition of τ_{flow} has not been rigorously validated but is used here as a reasonable starting point for demonstrating the overall methodology. The k/ε field for the shear layer formed at the downstream lip of the flameholder is shown in Fig. 3 below. k/ε values reach a minimum in the shear layer close to the lip of the flameholder. For this simple rig configuration, we assume that this region controls stability and we evaluate τ_{flow} *f*or *Da* in this critical region. For the conditions considered here τ_{flow} is in the range 0.2 to 2 ms.

In the current demonstration, non-reacting CFD calculations are used to calculate τ_{flow}. The error associated with this assumption is currently unknown. In the future we plan to quantify this error by comparing τ_{flow} values generated using non-reacting and simple reacting-flow CFD calculations.

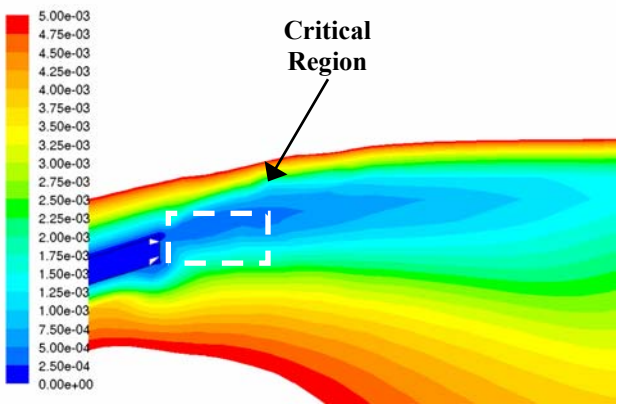

Figure 3. k/ε field close to the trailing edge of the flameholder. k/ε values are minimum in the shear layer close to the flameholder and reaching values ~0.5 ms.

VIII. Chemical Timescale

τ_{chem} values are calculated based on ignition delay time calculations made using using a perfectly stirred reactor model. Calculations are made in CHEMKIN® using the San Diego propane mechanism. All calculations are for propane-air at 1 atm. Ignition delay calculations are highly sensitive to initial temperature. Plee[18] has argued that the maximum temperature in the system should be used as the initial temperature, although how to determine this temperature is another open question. Here we use adiabatic flame temperature (T_{ad}) as the initial temperature in order to be as objective as possible. Using T_{ad} results in the fastest possible values for τ_{chem} and probably under-predicts τ_{chem} relative to actual conditions.

An ignition delay time curve is shown for propane air for $\Phi = 0.3$ in Fig. 4 below. Ignition delay is calculated based on peak OH concentration, which is a common convention. For this very lean equivalence ratio, τ_{chem} is relatively slow, ~2 ms. τ_{chem} is calculated as a function of Φ in this way to generate a curve relating τ_{chem} and Φ for lean propane-air, Fig. 5 below. The relationship is highly nonlinear.

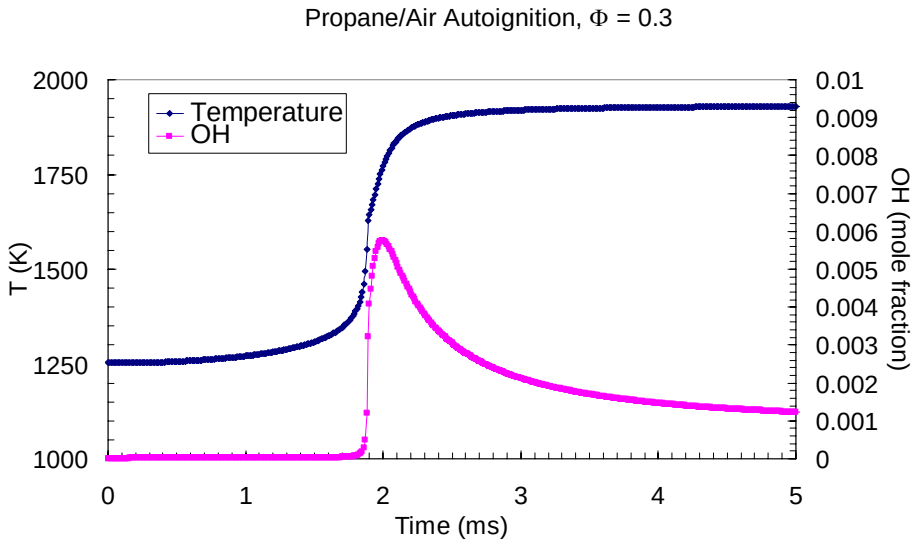

Figure 4. Propane-air ignition delay calculation, $\Phi = 0.3$, $T_o = T_{ad}$.

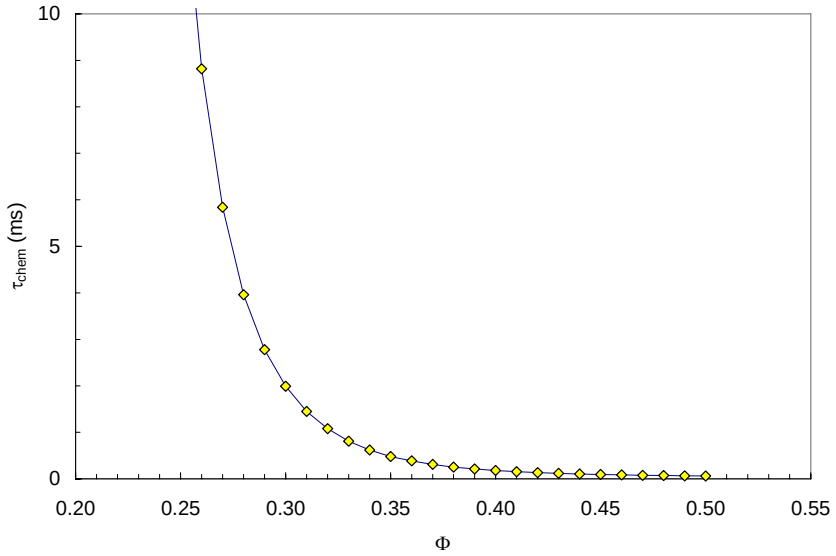

Figure 5. τ_{chem} as a function of Φ for lean propane-air.

IX. LBO Predictions

For the AFRL in-house rig configuration, we evaluate *Da* in the critical region as shown in Fig. 3. Our stability limit is simply *Da* = 1. Our predictions are plotted against measured values and values generated using the existing correlations described above in Fig. 6 below. Values for King are not shown because King's correlation does not apply to the temperature range for the HIT rig data and returns non-physical (rich) LBO Φ. As expected, the timescale correlations of Ozawa and Plee outperform the empirical correlations of King and DeZubay. The existing timescale correlations are significantly offset in Φ from the measured values. The stratification in the Plee data is grouped by inlet temperature.

The current method does a good job of predicting this configuration. This result should be treated with caution due to the potential mixing issue described above. The reported LBO Φ values are unusually low, with many data points falling below Φ = 0.4, lending credence to the possibility of a fuel mixing problem. In addition, many assumptions were made in this demonstration of our methodology, such as perfect mixing and assuming an initial temperature of T_{ad} for ignition delay calculations, that could prove faulty when this methodology is applied to more realistic configurations. We would like to emphasize that we are presenting an improved methodology, and that there are many open questions regarding how the methodology should be applied for a particular configuration. For the current configuration, our methodology was developed and implemented so that LBO predictions would match known experimental values. A useful design tool must be able to accurately predict various configurations without *a priori* knowledge of the outcome. It is also very interesting to note that the existing correlations predict LBO over a broad range of values, indicating the predictive inconsistency of the existing approaches independent of our predictions.

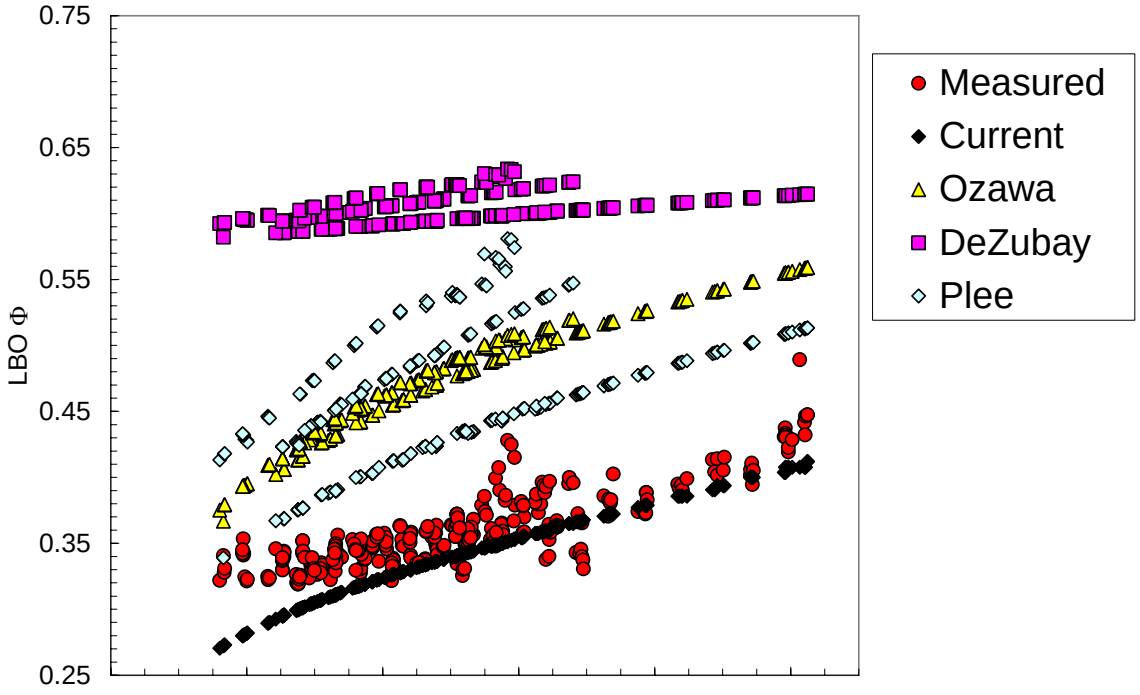

Figure 6. Lean blowout Φ predictions using the current method and several existing correlations for the AFRL in-house rig.

In this demonstration, stability was determined based on *Da* values at a particular location in the flow. For future analyses of more complex geometries, we plan to develop a more advanced approach where the local spatial distribution of *Da* is used to determine stability, as opposed to a single local value for *Da*. In this way more advanced criteria can be applied to determine stability. When implementing this approach, we plan to form a probability density function (PDF) for *Da* describing the spatial distribution of *Da* in the reaction zone. Stability

predictions could then be made based on this PDF. For example, if local extinction were to occur for a certain volume of the volume of the flow (i.e., if a certain volume has $Da < 1$), blowout would occur.

Similarly, a model incorporating unsteady flow effects could be developed based on both the spatial and temporal variations in *Da* in the reaction zone. For flames where vorticity plays a key role in blowout, temporal variations in *Da* may be as critical as spatial variations in determining stability.

X. Challenges and Future Work

Progress in this research program to date reflects the scope of a relatively small Phase I SBIR research program. The methodology has been developed and demonstrated for a single, simplified configuration. This exercise has raised many important questions on how this methodology should be implemented. What are the critical location(s) in an augmentor that determine stability? What temperature should be used when making ignition delay calculations? Can cold-flow CFD simulations be used to calculate τ_{flow} values with reasonable accuracy? When can the perfect mixing assumption be applied, and when should a PaSR reactor be used? How should fuel penetration effects be incorporated into the model? In the future we hope to address these questions by implementing our approach on a broad range of configurations, including other rig configurations and realistic combustor configurations.

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